Gondwana Research xxx (2015) xxx–xxx

Contents lists available at ScienceDirect

Gondwana Research

journal homepage: www.elsevier.com/locate/gr

Focal depths and mechanisms of shallow earthquakes in the Himalayan–Tibetan region

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ARTICLE INFO

Article history:
Received 25 April 2015
Received in revised form 30 June 2015
Accepted 4 July 2015
Available online xxxx

Keywords:
Tibetan plateau
Earthquake focal depths
Focal mechanisms
Seismogenic thickness

ABSTRACT

The complexity of the Himalayan–Tibetan lithospheric deformation is evident from widespread seismicity and diverse focal mechanism solutions. Here we investigate the focal depths and fault plane solutions of 97 moderate and shallow earthquakes in the Himalayan–Tibetan region by modeling teleseismic P-wave and its tailing surface reflections pP and sP. Earthquakes in central Tibet are restricted to the upper crust and originate dominantly by strike-slip faulting, in agreement with the low P-wave velocity layers in the lower crust and the strong S-wave attenuation zones in the uppermost mantle. In northern and southern Tibet, where the Asian and Indian plates descend beneath central Tibet, earthquakes appear to be distributed throughout the thickness of the crust and exhibit dominantly reverse faulting. We incorporate well-estimated focal depths of 127 additional earthquakes from previous studies to estimate the seismogenic thickness (*Ts*) of the study region. The resulting pattern of *Ts* is found to be rather flat for central and northeastern Tibet and highly variable along the strike of the Himalayan foreland.

1. Introduction

The collision between the Indian and Eurasian Plates followed by the subduction and closure of the Neo-Tethys Ocean formed the Himalayas and the Tibetan plateau, the world's largest orogenic belt and highest plateau (Fig. 1). The elevation of the Tibetan plateau exceeds 5 km within an area of 2,500,000 km^2 (Amante and Eakins, 2009). Its crust is 50–80 km thick, nearly twice as much as the average Moho depth of the world (Shin et al., 2009). From north to south the Kunlun, Songpan-Ganze, Qiangtang, and Lhasa terranes exemplify the remarkable horizontal inhomogeneity of the plateau (Yin and Harrison, 2000).

The United States Geological Survey (USGS) earthquake catalog includes about 1500 shallow ($H \le 50$ km) earthquakes and 700 intermediate-depth ($50 < H \le 300$ km) earthquakes with $M_W > 5.0$ from the past 50 years (Fig. 2). Since 1900, 8 earthquakes of $M_W \ge 8.0$ and 52 earthquakes of $7.0 \le M_W < 8.0$ have occurred (Hatzfeld and Molnar, 2010). The whole region of the plateau accommodates shallow earthquakes, while intermediate-depth seismicity is concentrated at the Indo-Burma and Pamir-Hindu Kush subduction zones, which are located at the eastern and western Himalayan syntaxes, respectively. The diversity of focal mechanism solutions for both shallow and intermediate-depth earthquakes indicates intricacy of the current stress field beneath the Himalayan–Tibetan region.

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The significant differences between earthquake catalogs illustrate that the routine measurements of earthquake source parameters are highly uncertain, especially for shallow earthquakes (Fig. 3). The catalog from China Earthquake Network Center (CENC) relies on arrival times of regional seismic network which provides a good constraint on focal depths for earthquakes within the network. However, differences in depth estimates for nearly 15% of earthquakes are larger than 20 km due to scarce station coverage and complex velocity structure in the Himalayan–Tibetan region (Fig. 3(a1)). The USGS preliminary determination of epicenters (PDE) provides earthquake catalog based on arrival times of teleseismic body waves. This catalog is as much accurate as that of CENC catalog because the combination of later phases improves the accuracy of the earthquake locations (Fig. 3(b1)). The global Centroid Moment Tensor (gCMT) locations are updated USGS PDE locations using low-pass-filtered long-period waveforms (Ekström et al., 2012) (Fig. 3(c1)). The EHB catalog provides the best depth estimates based on various teleseismic arrival times for earthquakes up to the end of 2008 (Engdahl et al., 1998). Focal depths are better constrained by modeling the broadband waveforms as the depth phases are easily distinguishable than in long-period records.

Location accuracy of focal depths directly affects our understanding about the physical mechanism of the seismicity and the deep structure of the Earth. The controversy on the lower crustal or upper mantle earthquakes beneath the Himalayan region comes from the measurement uncertainty of the earthquake location and the crustal thickness (Chen and Yang, 2004; Jackson et al., 2008). A detailed investigation of the crustal flow layer, which is distinguished from the seismogenic zone, requires accurate knowledge of the earthquake location

http://dx.doi.org/10.1016/j.gr.2015.07.009
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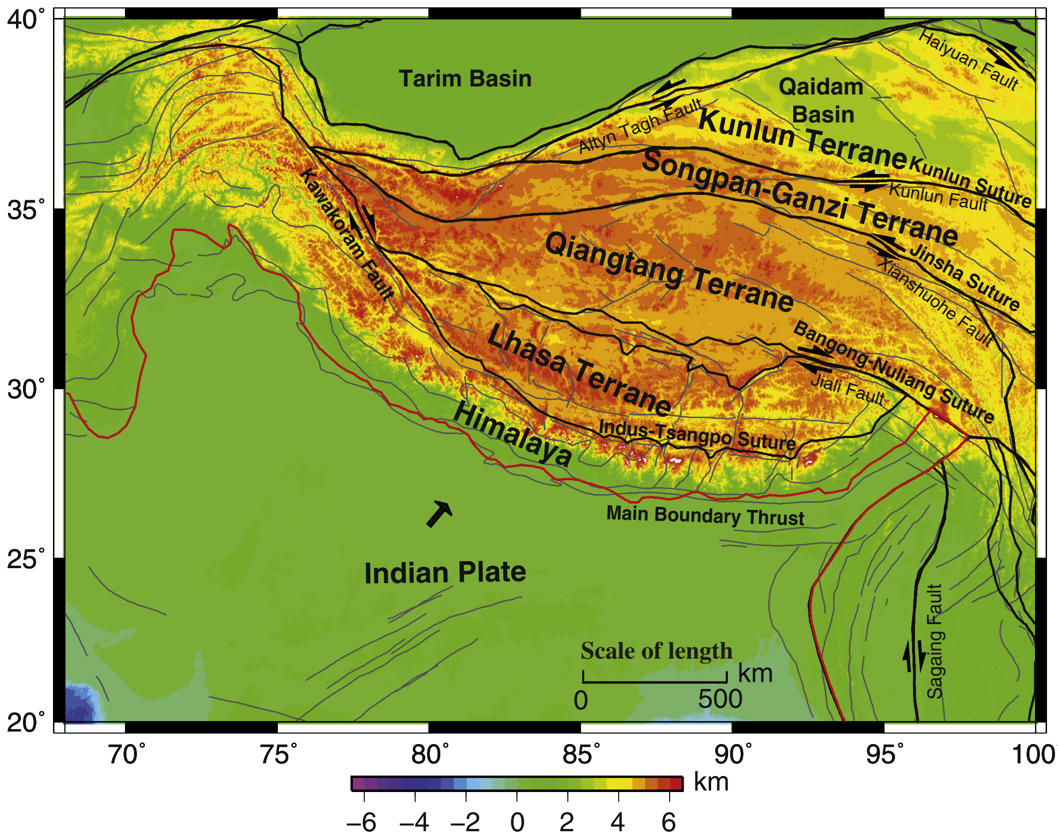

Fig. 1. Tectonic map of the Himalayan–Tibetan region. Red and black lines are plate and terrane boundaries, respectively.

(Klemperer, 2006). Similarly, understanding the structure of subducted slab requires constrains from earthquake location and focal mechanism solutions (Bai and Zhang, 2015).

In this paper, we estimate focal depths and focal mechanism solutions of 97 shallow earthquakes in the Himalayan–Tibetan region using teleseismic P-wave modeling. These 97 events account for more than 95% of moderate earthquakes ($5.4 \le M_W < 7.0$) occurred since 1990. These events occurred at different regions hence suitable for providing constrains for various tectonic implications. The manifold implications of this study would provide new constrains on the deep

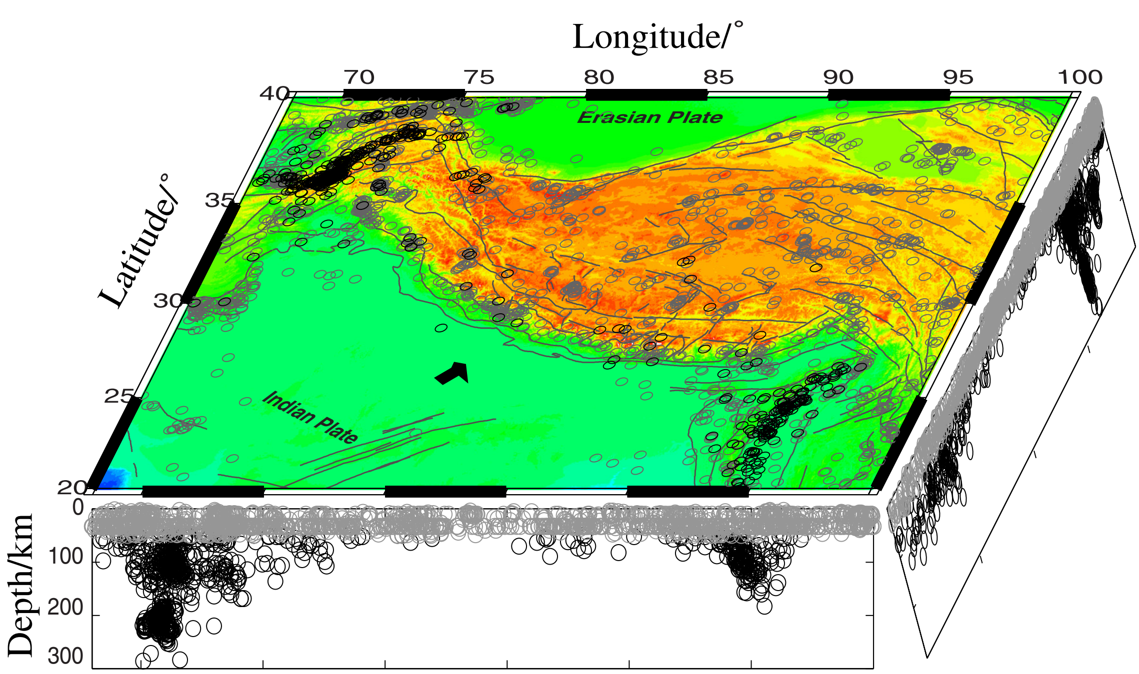

Fig. 2. Distribution of earthquakes of Mw ≥ 5.0 that occurred in the past 50 years. Gray and black circles show shallow and intermediate-depth earthquakes, respectively. The depth scales in cross-sections are twice of the actual size.

Please cite this article as: Bai, L., et al., Focal depths and mechanisms of shallow earthquakes in the Himalayan–Tibetan region, Gondwana Research (2015), http://dx.doi.org/10.1016/j.gr.2015.07.009